Fabrication and Characterization of MWCNT-Based Bridge Devices

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Abstract—Carbon nanotubes (CNTs) are one of the most actively researched structural materials due to their interesting electrical, mechanical, and chemical properties. Unlike single walled carbon nanotubes (SWCNTs), little work has been focused on multi-walled carbon nanotubes (MWCNTs) and their potential for practical devices. Here, we have fabricated bridge-shape devices integrating MWCNTs (> 50 nm in outer diameter) using three processes: optical lithography, electron beam-induced platinum deposition, and surface micromachining. Each device consists of a doubly-clamped nanotube suspended over gold electrodes on a highly conductive Si substrate. The suspended nanotubes are characterized individually using Raman spectroscopy and semiconductor parameters analysis and, overall, show, high crystallinity and low electrical resistance. The spring constants of doubly-clamped nanotubes were characterized using atomic force microscopy force-displacement measurements, with values as high as 70 N/m observed. Highly stiff MWCNTs are promising for a variety of applications, such as resonators and electrical interconnects. Through simulations, we estimate the resonance frequencies and pull-in voltages of these suspended nano-structures. The dependence of key parameters, such as the nanotube's length, Young's modulus, axial stress, and wall thickness is also discussed.

Index Terms— Carbon nanotubes, Clamps, Suspensions, Force measurement

I. INTRODUCTION

Suspended doubly-clamped structures have wide range of applications such as mass sensing [1], force detection [2], chemical/biological sensors [3], mechanical computing

components [4-7], and electrical interconnects [8, 9]. Various materials, such as Si [10], SiC [11], AlN [12], and InAs [13] have been used to realize micro/nano bridges [14] for these applications. With outstanding physical properties, such as a Young's modulus greater than 1TPa [15], an electron mobility greater than $100,000 \text{ cm}^2/\text{Vs}$ [16], and a thermal conductivity of up to 6000 W/m.K [17, 18], CNTs could easily surpass Si, SiC, AlN and InAs as the structural material of choice for micro/nano devices. These tubular structures can operate at resonance frequencies as high as 39 GHz [19] with quality factors up to 5 million [20], which makes them suitable for sensitive applications, such as mass spectrometer with a resolution of $10^{-25} \text{ kg/Hz}^{-1/2}$ [1]. To present, most of the efforts have been focused on SWCNTs-based devices [1, 15, 16, 20-25]. However, MWCNTs bear several advantages including higher resonance frequencies and stiffness, higher chemical inertness, and simpler and less expensive synthesis techniques [26]. Further, MWCNTs are less prone to bundle and can be processed post-synthesis to optimize their graphitization degree [27]. When filled with an inorganic compound and suspended from two metal electrodes, it is possible to analyze the dynamics of current conduction and heat dissipation [28].

In the majority of reported bridge structures, the CNT is directly grown on the device substrate at the desired location by chemical vapor deposition (CVD) [22]. However, this method requires horizontally aligned growth, a process that remains unreliable with regards to the final end-to-end direction as well as length/deformation of each suspended nanotube. Another point to consider is adhesion. In the CVD direct growth approach, one relies on weak van der Waals forces or post-synthesis deposition and patterning of metal electrodes using e-beam/photo-lithography [4, 5, 22, 29] to realize the interconnector. Interestingly, most of the reported devices are single to few walled CNTs with outer diameter less than 5 nm or MWCNTs with outer diameter typically less than 50 nm. Furthermore, when the CVD approach is used, it is rather challenging to correlate microstructural, mechanical, and electrical analyses for a single interconnect nanotube in bridge-like configuration. All these drawbacks can be eliminated with discrete CNT manipulation and fabrication inside a scanning electron microscope (SEM) [23] and the use of larger, well-structured MWCNTs. Because of their high stiffness, these structures can boost the operating resonance range of bridge-like devices from tens of MHz to GHz. Also,

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they provide lower contact resistance/losses and withstand higher current densities. Moreover, as they can be grown separately (i.e., ahead of device integration), MWCNTs can be thermally pre-treated to tailor their mechanical properties [27].

Here, we fabricate and characterize doubly-clamped MWCNT devices with outer diameters greater than 50 nm. We demonstrate a technique to clamp these large CNTs to Au electrodes using electron beam-induced deposition (EBID) of Pt for bridge-like devices with enhanced mechanical stability and low electrical resistance. For each bridge device, the structural, electrical, and mechanical characteristics are analyzed. These correlated data sets are then used to simulate the resonance frequencies and pull-in behavior of the CNTs.

II. EXPERIMENTAL PROCEDURE

A. Device fabrication

Fig. 1a shows a schematic (top and side view) of the steps used for fabricating the MWCNT nanoelectromechanical bridge device. N-type highly boron doped Silicon (100) wafer with resistivity of 0.001 to 0.005 Ωcm was used to form the gate electrode and the substrate. The wafer was subjected to thermal oxidation at 1000 $^{\circ}\text{C}$ for 5 minutes to grow 50 nm dry SiO_2 in order to electrically isolate the fabricated devices from the substrate (Fig. 1a (1)). Using plasma-enhanced chemical vapor deposition (PECVD), amorphous Si was deposited on the wafer forming the sacrificial layer (Fig. 1a (2)). The thickness of the amorphous Si is used to define the actuation gap of the device and can be varied as required. In our setup, devices with actuation gap as low as 200 nm were fabricated. Using standard optical lithography and reactive ion etching (RIE), an opening was made on the wafer by etching the amorphous Si and SiO_2 such that the portion of the Si substrate underneath is exposed (Fig. 1a (3)). A 100 nm layer of gold was deposited by physical vapor deposition (PVD) and patterned using another optical lithography step followed by lift-off. The gold was d.c. sputter deposited at 400 W of power and 4 mTorr argon pressure. The gold was patterned to form three electrodes, namely source, drain, and gate (Fig. 1a (4)). The gate electrode was deposited and patterned on the portion where the Si substrate was exposed while the source and the drain electrodes were patterned on the regions containing the amorphous Si above the SiO_2 . MWCNTs from Sigma Aldrich (Cat No. 659258) synthesized by chemical vapor deposition were dispersed in isopropanol alcohol (IPA) with concentrations of about 2 mg/L by ultra-sonication for 30 minutes, and then drop-casted onto the Si wafer (Fig. 1a (5)) [30]. The wafer was continually ultra-sonicated as the IPA was air-dried. This technique reduced the re-coagulation of the dispersed MWCNTs during the air-drying process. The substrate was then loaded into a FEI Helios NanoLab 400S FIB-SEM system equipped with high-resolution SEM column and precursor gas injection system for Pt deposition. SEM imaging was used to identify the MWCNTs that were self-aligned across the source and drain electrodes. The ends of the nanotubes were clamped to the electrodes using EBID (Fig. 1a(6)). Trimethyl(methylcyclopentadienyl)platinum

Fig. 1. Fabrication of a MWCNT based nanoelectromechanical device. (a) Schematic of the steps (top and side view) used for fabrication. The device is fabricated using optical lithography and e-beam assisted Pt deposition clamping of CNT. (b) False color SEM micrograph of the MWCNT device acquired at 52 degree tilt. The two gold pads form the source and drain electrodes while the Si substrate with 50 nm SiO_2 forms the gate electrode probed through a third gold pad.

(MeCpPtMe₃) was used as the precursor gas for the Pt deposition. The electron-beam was set at 5 kV of landing voltage and 86 pA of current. The SEM column consists of 8 apertures varying from 8 to 64 μm . The chosen beam current corresponds to a beam aperture of size 16 μm . At 5 kV, the spot size on the sample surface was about 1 nm. The current dosage was set at 28.88 nC/ μm^2 with dwell time of 1 μs . The deposition was done in serpentine pattern with a 32 nm pitch and 0 % overlap. This formed Pt clamps with optimized density minimizing the introduction of stress in the MWCNTs. The substrate was then ultra-sonicated in IPA for 2 s to remove the excess nanotubes, which are not aligned/clamped to the source drain electrodes. This also corroborates that the

nanotubes were clamped to the electrodes using electron beam-induced Pt deposition. Longer ultra-sonication caused clamped nanotubes to break off from the substrate and it was critical to limit it to around 2 s (Fig. 1a (7)). The nanotubes were then released by etching the amorphous Si in XeF₂ gas (Fig. 1a (8)). The wafer was exposed to XeF₂ (10%) and N₂ (90%) gas at 3 mTorr pressure for 80 s in four 20 s cycle to form free standing doubly-clamped MWCNT nanoelectromechanical bridge devices. Fig. 1b shows the false color SEM micrograph of the fabricated device. The width of Au electrodes used for clamping/contacting the nanotubes was set at 150 μ m.

B. Characterization

The suspended nanotubes were morphologically, electrically and mechanically analyzed. SEM imaging was used to study the external morphology of the nanotubes and the quality of the clamps. All the images were acquired at 5 kV landing voltage and 43 pA of current. The sample for transmission electron microscope (TEM) analysis was prepared by using the same solution as used for fabricating the devices. Few drops of solution were drop-casted on to the holey carbon Cu grid. Bright field TEM images were collected on FEI Tecnai G² Spirit TWIN at 120 kV. TEM was used to analyze the defects, number of walls and spacing between the walls. Raman spectroscopy was used to study the crystallinity of the suspended individual nanotube bridges. Raman spectrum of the bridges were acquired on WITec Alpha 300RA at 532 nm laser source with 100X objective lens. To avoid potential damage, the power of laser was maintained below 2 mW. The MWCNT voltage-current curves and the leakage currents between adjacent Pt nano-lines were analyzed using Keithley 4200A-SCS semiconductor parameter analyzer by electrically probing across the Au electrodes. The voltage was swept from -2 to +2 V with current compliance of 100 μ A to prevent damage of the MWCNTs due to high currents. The devices (suspended beams and the Pt nano-lines) were annealed in a Buchi B-585 oven pumped down to 10 mTorr. After annealing, the pressure was kept constant until the devices were cooled down to room temperature. The electrical properties of 10 devices were studied and are presented. We also analyzed the mechanical stiffness (spring constant) of five devices by AFM imaging and force displacement (FD) curves acquired using a Park system AFM (XE-100). The topography of the devices were first acquired in non-contact imaging mode using non-contact Si tips (NCHR, diameter less than 20 nm) followed by FD measurements at the midpoint of the CNT in contact mode. During the FD measurements, the CNT is deflected at its midpoint using the AFM tip and the resistive force experienced by the tip is measured by a position sensitive photodetector. The spring constant of the AFM tips were measured by acquiring FD curves on highly polished Si substrates. At least five FD curves were acquired per devices and their average values are reported.

III. RESULTS AND DISCUSSIONS

Ahead of integrating the MWCNTs in the devices, structural

Fig. 2. TEM micrographs of a representative MWCNT (a) Low magnification image showing a 6 μ m long nanotube. (b) Magnified image of the nanotube in (a) showing the internal structure. (c) High resolution view of the section marked in (b) showing the well-graphitized walls and defects/gaps in the nested tubes.

Fig. 3. A histogram showing the distribution of the outer diameter over 400 MWCNTs. The outer diameters ranged from 40 to 320 nm with about 80% of the nanotubes between 100 to 200 nm.

characterization was performed to evaluate parameters such as length, internal/outer diameters (wall thickness), density of structural defects, chemical purity (e.g. absence of catalyst remainders such as metal particles) and graphitization degree. All of these are known to affect the physical properties of individual MWCNT (e.g. Young's modulus) which, when applied to the present case, define the device performance parameters such as resistance, resonance frequency, and pull-in voltages. In Fig. 2, both the morphology and the internal structure of a MWCNT is visible. Overall, the nanotubes presented have outer diameters varying from 40 to 320 nm, with the majority (80%) of them within the range of 100 to 200 nm. Fig. 3 shows the distribution of the outer diameters of 400 nanotubes. Their inner diameters were found to be as low as 5 nm (resembling near solid rods) to tens of walled

nanotubes. The majority of the nanotube lengths range from 5 to 11 μm as specified by the vendor. Although there were shorter nanotubes (possibly originated during the dispersion process) and longer than the specified length, this fact was not relevant since the length of interconnects in the presented devices were defined by the width of the trench. TEM showed that the internal structure of the MWCNTs studied is akin to those produced via the arc-discharge method, which is known to originate highly graphitized nanotubes [31]. The presence of small amounts of amorphous carbon was detected in high resolution TEM micrographs (Fig. 2b). The average interlayer distance was 0.3425 nm, close to the distance between graphene layers in graphite (0.335 nm). The ends of the nanotubes have a cone-like structure, which is usually explained by the presence of pentagon defects in the hexagonal carbon lattice [32]. Note that the higher density of pentagons at the tips would not be deleterious for the device characteristics (as the ends are clamped and are far from the free standing portion of the CNT in the device).

Fig. 4 shows the current-voltage characteristics of ten suspended MWCNT devices. Their morphological and electrical characteristics are summarized in Table I. The length of the interconnecting nanotubes vary from about 1.5 to 5 μm with their outer diameter ranging from 100 to 240 nm. Remarkably, we noticed up to $\pm 30\%$ variation in the outer diameter within a single nanotube. The nanotubes have either linear or non-linear electrical behavior. As expected the nanotube devices with linear behavior had lower electrical resistance, between 5-8 k Ω . The MWCNTs with non-linear current-voltage curves had higher electrical resistance varying from 17 to 32 k Ω . The resistance values in Table 1 are measured at 0.5 V. It should be noted that the resistance decreases with the increase in voltage for the devices with non-linear characteristics (not a constant value). We report the resistance values at 0.5 V to provide a comparison. Ideally, MWCNTs have metallic behavior along with linear I-V characteristics even though they may comprise of both semiconducting as well as metallic walls rolled up within themselves (metallic walls mask the behavior of the semiconducting walls). The non-linear behavior may be due to the presence of dominant number of semiconducting walls. Due to the presence of semiconducting walls, their electrical resistance decreases with voltage due to the electro-thermal carrier charge generation in the nanotubes [33]. Another possible explanation is the presence of an outermost semiconducting wall, which forms Schottky-barrier [34, 35], resulting in non-ohmic contact with non-linear electrical characteristics. On the contrary, the presence of outermost metallic wall/s in the MWCNTs may form ohmic-contacts resulting in linear electrical characteristics. It should be noted that the present MWCNTs do not possess trans-conductive properties with respect to change in gate voltage irrespective of having linear or non-linear electrical characteristics (Fig. 4b). When considering electromechanical applications, the low resistance in the metallic CNTs is preferred as it yields reduced electrical losses in the device. An important point in EBID fabricated devices is the curing step. Here, the effect of

Fig. 4. (a) Current-voltage characteristics of ten MWCNT devices; the nanotubes show either linear or non-linear behavior. (b) The gate voltage has no effect of the devices showing zero transconductance. The drain-source was biased with a d.c. of 0.1 V. (c) Current-voltage curves highlighting the changes in the electrical behavior of device '6' after stepwise annealing from 100 °C to 300 °C.

TABLE I
Summary of electrical and morphological properties of the MWCNT devices.

Device	Length (μm)	Outer diameter (nm)	Resistance at 0.5V (kΩ)	Electrical behavior
1	1.71	112-156	7.8	linear
2	1.9	108-155	5.3	linear
3	1.9	141-200	6.3	linear
4	2.83	115-153	5.7	linear
5	4.96	127-168	5.6	linear
6	2.79	189-230	17.4	non-linear
7	2.54	102-120	18	non-linear
8	1.89	99-115	31	non-linear
9	2.06	112-142	29.3	non-linear
10	1.78	114-145	22.7	non-linear

annealing on the platinum-CNT contact resistance was studied. The devices were annealed stepwise for 30 minutes, in 10 mTorr pressure at 100, 200 and 300 °C, as shown in Fig. 4c for device '6'. While there was negligible change in the electrical resistance after annealing at 100 °C (17.6 k Ω), the processes at 200 and 300 °C led to readable variations, where the electrical resistance increased to 30.6 and 41.7 k Ω ,

Fig. 5. Characterization of overspray and leakage currents in EBID of Pt. (a)-(e) SEM micrographs of two adjacent EBID of Pt lines spaced by 1000, 500, 250, 100 and 50 nm, respectively. (f) High magnification SEM micrograph of two adjacent EBID of Pt lines spaced by 50 nm. (g) Leakage resistance as a function of gap spacing before and after annealing at 300 °C in 10 mTorr vacuum pressure. The resistances reported are at 2V.

respectively. Interestingly, this observation contrasts to a previous report where the conductivity of the platinum-CNT contact, also fabricated through EBID, was improved with annealing [36]. In the present case, the overall resistance increase may be due to the stresses derived from the thermal expansion coefficient mismatch of the platinum-CNT-gold layers and/or due to the thermal oxidation of the CNT carbon. It was noticed that when the devices were annealed for 1h at 300 °C, the nanotubes were cleaved off at the platinum-CNT contact, thereby forming an open circuit. This corroborates our assumption of the thermal stress induced in the contacts. Taken together, the need for annealing can be overlooked. The platinum was efficient in clamping the nanotubes to the gold electrodes, resulting in low resistance Au-CNT contacts. Microscopic four-point probe measurements will improve understanding of the role of Pt/Au-CNT contact resistance [37]. However, performing such measurements was not possible due to the free-standing nature of the structure. Also, alternate to EBID of Pt, ion-beam induced deposition (IBID) of Pt clamps can be used [36]. Although the IBID method has the advantages of lower resistivity and faster deposition rate, it suffers from resulting in non-intentional ion implantation and ion-milling/sputtering.

One of the important factors to consider in EBID is the presence of overspray [38-40], where the deposited material exceeds the dimensions defined by the deposition beam raster due to the action of secondary electrons. The overspray may spread up to few microns and can lead to leakage currents between adjacent Pt deposits. To characterize this phenomenon, two adjacent Pt lines were deposited and the

Fig. 6. Nano-mechanical characterization of individual nanotubes using AFM imaging and force-displacement measurements. (a) Schematic of the setup used for AFM imaging and for obtaining the force-displacement curves. Side view 3-dimensional surface map of the device '15' is also shown. (b) Topographical image of device '15' acquired using non-contact mode. The mid-point of the MWCNT where the FD curves are obtained is highlighted by a black cross. (c) A typical FD curve (acquired on device '15') showing both the approach and withdrawal traces by the Z-scanner of the AFM. The slope of the curve after contacting the CNT surface provides the effective spring constant of the AFM tip and the device.

leakage current was measured using two-probe I-V measurements. Figs. 5a-e show various pairs of adjacent Pt lines with spacing ranging from 1000 to 50 nm. Five samples per spacing were fabricated and characterized. The resistance between the Pt lines was measured before and after annealing (at 300 °C, 10 mTorr vacuum), and their average values are

TABLE II

AFM force-displacement measurements and Raman spectroscopy based analysis of five MWCNT based devices.

Device	Length (μm)	Outer diameter (nm)	Spring constant of CNT (N/m)	Spring constant of AFM tip (N/m)	I _D /I _G Ratio
11	4.7	170.3 – 200.5	3.9	103	0.193
12	4.6	100 – 120.5	7.7	103	0.223
13	3.6	178-216.8	25.6	103	0.459
14	1.5	142- 161.8	72.6	96.5	0.312
15	2.9	171.1- 200.1	17.2	113.2	0.312

reported in Fig. 5g. When the spacing was 1 μm or above, the resistance was 10 GΩ or higher demonstrating an open electrical path with leakage current mainly due to thermal noise. With 500 nm spacing, the samples still showed an open path before annealing. However, the resistance dropped to 1 GΩ upon thermal exposure, confirming the presence of over-sprayed Pt connectivity between the adjacent Pt lines. The change in resistance may be attributed to the removal of carbon impurities or/and crystallization of carbon and Pt in the over-deposits [41]. With further reduction in the line spacing up to 50 nm, the resistance consistently decreased, particularly in the annealed samples. However, even at a spacing as low as 50 nm, the resistance was 8 MΩ, illustrating well the absence of major leakage currents, in contrast to analogous systems [38]. Based on the above, our EBID clamping technique is more reliable when using an inter-device spacing of about 500 nm. Due to the overspray, the Pt/C mix can be deposited on the free standing portion of the CNT. This will add mechanical stiffness (due to increased mass) and a certain degree of residual stress, in turn affecting the curvature of the free-standing CNT. In the present, no noticeable change in the CNT curvature was observed. Finally, the electrical properties of the device could be affected, where the Pt and C atoms could act as surface dopants and provide conduction paths on the suspended portion of the CNT. However, even with the spacing as low as 50 nm, the resistance due to the over-sprayed film was in the MΩ range, which is significantly higher than the resistance of the CNTs, showing thus a negligible effect of Pt overspray on the measured resistance CNT devices.

We characterized five devices for their mechanical properties using AFM imaging and FD measurements [42-45]. Fig. 6 and Table II summarize the setup and the mechanical properties of these five devices, respectively. Fig. 6a shows a schematic of the setup (along with the cross-sectional AFM surface micrograph of device ‘15’) used for imaging as well as acquiring the FD curves. Fig. 6b shows the topography of device ‘15’ acquired with a non-contact imaging mode. After acquiring the image, the FD curves were obtained at the region of interest (mid-length point of the nanotube, highlighted with a black cross). Fig. 6c shows a typical FD curve (acquired on device ‘15’), consisting of both approach (in red) and withdrawal (in blue) processes. The tip experiences 0 N force

Fig. 7. Raman spectrum of device ‘11’ highlighting the peaks at around 1348 (D-band), 1575 (G-band) and 2698 cm⁻¹ (2D-band), showing the typical signature of MWCNT. The low value for the I_D/I_G ratio along with the narrow G-band demonstrates the high crystallinity of the nanotubes.

as the tip travels in air while approaching the CNT. When the AFM tip is very close to the nanotube, it snaps to contact experiencing negative force due to the attractive van der Waals force exerted by the CNT. As the z-scanner of the AFM extends further down, the tip deflects (upwards) experiencing a positive force while pushing the nanotube down. The slope of the FD curve (acquired after the tip has contacted the CNT) provides the effective spring constant (k_{eff}) of the CNT and the AFM tip (in series). The spring constant of the CNT (k) can be obtained from;

$$k = \frac{k_{eff} \times k_c}{k_c - k_{eff}} \quad (1)$$

where k_c is the spring constant of the AFM tip. The z-scanner is then moved up in the ‘z’ direction and the withdrawal FD curve is acquired. The FD curves acquired have linear slopes along with near identical approach and withdrawal curves showing low stiction/adhesion between the nanotube and the tip. Table II summarizes the device dimensions and the measured spring constants. The values range between 3 to 70 N/m, which is significantly higher when compared to the spring constants of previously reported MWCNT devices [42, 43, 46]. The spring constant of the AFM tips used were about 100 N/m. We also acquired Raman spectra on these suspended MWCNTs and reported their I_D/I_G ratios. This provides an assessment of the nanotube’s structural/graphitic property after its integration in the device. Fig. 7 shows a typical Raman spectrum of a suspended CNT (device ‘11’), with peaks at around 1348, 1575, and 2698 cm⁻¹, corresponding to the D-, G- and 2D-bands, respectively [47]. The low intensity of the D-band peak confirms that there is negligible structural disorder in the nanotubes. This is corroborated by the intense narrow G-band. Finally, the relatively high intensity of the 2D-band peak points to the presence of long-range order besides reflecting the metallicity of the MWCNT [48]. The D- to G-band intensity ratio is low, varying from 0.19 to 0.46, confirming the crystallinity of the devices.

Fig. 8 shows the simulated resonance frequencies and static pull-in voltages of the fabricated devices, using a lumped-parameter model [49]. Different values of Young’s modulus

(E), lengths (L), axial stress (σ), inner (d_i) and outer (d_o) diameters of the nanotubes are used in the model, which lie within the range of the fabricated device parameters. High resonance frequency are desirable for several applications such as high speed and low energy electromechanical computing. The nanotubes are assumed to be free of curvature and have uniform diameter. The spring constant k of the nanotubes is given by [49];

$$k = \frac{384EI}{L^3} + \frac{8.32\sigma A}{L} \quad (2)$$

where I = moment of inertia of hollow cylinders given by

$$\frac{\pi}{64}(d_o^4 - d_i^4), \text{ and } A = \text{cross section area given by}$$

$$\frac{\pi}{4}(d_o^2 - d_i^2). \text{ Using equation (2) and the spring constants}$$

measured using AFM, the Young's modulus of the CNTs were estimated (Table III). Note that here the inner diameters of the CNTs are not known, since the clamped CNTs were not suitable for TEM analysis. The assumed inner diameters of the devices are shown in Table III. The resonance frequency f is calculated by [49];

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{0.7674\rho AL}} \quad (3)$$

where ρ is skeletal density (2600 kg.m^{-3}) [50]. The pull-in voltages are simulated using [36];

$$V_{\text{pull-in}} = \sqrt{\frac{8kg^3}{27\epsilon A_o}} \quad (4)$$

where g = actuation gap fixed at 200 nm, A_o = CNT-gate electrode overlap area given by $0.5\pi d_o L$, and ϵ = permittivity of free space ($8.854 \times 10^{-12} \text{ F.m}^{-1}$). Fig. 8a shows the change in the resonance frequency with the Young's modulus values varying from 0.01 to 0.5 TPa (based on the AFM based estimated Young's modulus in Table III), and the lengths varying from 1 to 5 μm . The inner and outer diameters are fixed at 110 and 150 nm, respectively, with 0 axial stress. Fig. 8b shows the change in resonance frequency for different values of inner (5 to 245 nm) and outer (60 to 250 nm) diameters (length fixed at 2 μm , Young's modulus fixed at 0.25 TPa, and 0 axial stress). Fig. 8c shows the change in resonance frequency for different axial stresses (-3 to 9 GPa) for varying lengths (1 to 5 μm) with Young's modulus, inner and outer diameters fixed at 0.25 TPa, 110 and 150 nm, respectively. Correspondingly, Figs. 7e, f, and g show the change in the pull-in voltage for different Young's modulus (0.01 to 0.5 TPa) and lengths (1 to 5 μm), for different inner (5 to 245 nm) and outer (60 to 250 nm) diameters, and for different axial stresses (-3 to 9 GPa) and lengths (1 to 5 μm), respectively. Negative stress implies compressive stress and positive stress implies tensile stress. With the increase in the Young's modulus of the nanotubes, the device resonance frequency and pull-in voltage increases almost linearly. However, with the increase in the length of the nanotubes, the resonance frequency and pull-in voltage decrease non-linearly. For a fixed inner diameter, when the outer diameter of the

TABLE III
Estimation of Young's modulus based on AFM based spring constants

Device	Average outer diameter (nm)	Assumed inner diameter (nm)	Estimated Young's modulus (GPa)
11	185	10 – 165	20 – 54
12	110	10 – 90	270 – 490
13	197	10 – 177	42 – 120
14	152	10 – 132	24 – 56
15	185	10 – 165	19 – 52

Fig. 8. Lumped parameter model results of the MWCNT based suspended bridges. (a) The change in resonance frequency of the device with the change in length and Young's modulus of the nanotubes. (b) The change in resonance frequency of the device with the change in inner and outer diameters of the nanotubes. (c) The change in the resonance frequency of the device with change in axial stress for different device lengths (d) The change in electrostatic pull-in voltage of the device with the change in length and Young's modulus of the nanotubes. (e) The change in electrostatic pull-in voltage of the device with the change in inner and outer diameters of the nanotubes. (f) The change in the pull-in voltage of the device with change in axial stress for different device lengths.

nanotubes is increased, the resonance frequency increases linearly while its pull-in voltage increases almost linearly. For a fixed outer diameter, when the inner diameter of the nanotubes is increased, the resonance frequency of the device increases non-linearly, while the pull-in voltage decreases non-linearly. This is because, with the increase in the inner diameter, the stiffness and the mass of the nanotubes are reduced. The pull-in voltage decreases due to the decrease in the stiffness, irrespective of mass change. However, the

frequency is affected by both mass and stiffness, where the frequency increases with decrease in mass and increase in stiffness. When the inner diameter is increased, the impact of reduction in mass overtakes the impact of reduction in stiffness causing the frequency to increase. Therefore, a SWCNT with large diameter are better suited for high frequency, low power nanoelectromechanical devices. However, the reported SWCNTs are typically less than 5 nm in outer diameter [1, 16, 19-23] limiting their functionality. Therefore, MWCNTs with large inner diameters [51, 52] are suited for the desired properties. Also, MWCNTs have added advantages of chemical inertness and high purity compared to single walled CNTs and are suitable for harsh environmental applications with negligible difference in terms of performance when compared to single walled CNTs [26, 50]. With the increase in Young's modulus and decrease in the CNT length, the device frequency increases but at the cost of higher pull-in voltages (actuation voltage). Also, with the increase in the axial stress of the nanotubes, the device resonance frequency and pull-in voltage increase linearly. Therefore, devices with tensile stress are suitable for high frequency applications. Such tensile stress can be induced by the gate voltage when the actuation gap of the device is greater than five times the diameter of the CNT [53], however, at the cost of higher actuation voltage. The simulated pull-in voltages range from few tens to hundreds of volts limiting their integration with CMOS-devices as static switches. However, such very high pull-in voltages is desirable for resonators and dynamic-mode applications [4, 5]. For static applications, such as switches, the device actuation voltages can be reduced by fabricating devices with lower actuation gap. This could be achieved via in-situ fabrication inside a SEM equipped with nano-manipulators [23], which also reduces the randomness presence in the CNT-IPA dispersion and drop cast technique. One should note that lumped-parameter modeling suffers lower accuracy and hence should not be used for final designs; but rather for initial designs and judgments. More complicated models, such as beam models, which account for the various nonlinear forces need to be considered for more accurate results [54-56].

As indicated, a potential use of such stiff and of very high pull-in voltage CNTs is resonators. The dynamic behavior of MWCNT in an oscillating electrical environment can be directly observed using field emission microscopy (FEM) [57], transmission electron microscopy (TEM) [25, 58], scanning force microscopy (SFM) [59], and scanning electron microscopy (SEM) [21] based imaging techniques. Photo-thermally excited MWCNT resonator detected using optomechanical heterodyne has also been demonstrated [60]. One of the key challenges/requirements for electrically detecting the resonance frequencies of these devices is to reduce the background parasitic currents (due to the common conductive Si as back gate-electrode providing conduction paths to the applied a.c. voltages) such that there is detectable output-to-noise ratio (during the resonating and non-resonating state). Although d.c. or a.c. frequency mixing technique [19, 22, 23] have been used to reduce the background parasitic currents, they are limited to single-walled semiconducting CNTs with transconducting property. Hence, the mixing technique is not suitable for the devices

reported here due to the non-transconductive nature of CNTs (as seen in Fig. 4b). One promising method to detect the resonance frequency using direct capacitive detection technique [4, 5] is to fabricate similar bridge structures on insulating substrates, such as quartz, with localized actuation gate electrodes [13].

IV. CONCLUSION

We successfully fabricated suspended MWCNT devices eliminating the need for high temperature processes. The nanotubes were clamped to the Au electrodes using electron-beam induced deposition of Pt, demonstrating good adhesion and Au-CNT electrical contacts. The interconnecting nanotubes used showed high crystallinity and non-linear and linear electrical characteristics. For the devices with Ohmic-response, the electrical resistance was as low as 5 k Ω . We further characterized the mechanical stiffness of five devices, which showed spring constants as high as 70 N/m. To understand the suitability of these systems for nanoelectromechanical applications, a lumped parameter model was used to simulate their performance. We found that their resonance frequency can range from 10 MHz to 2.2 GHz with pull-in voltages in the interval from 10 V to 2 kV (for devices with an actuation gap of 200 nm). Remarkably, the nanotubes with large outer and inner diameters showed the most promise for low power, and high frequency devices. Overall, the fabrication method described here provides a promising path for fast, low power CNT-based devices utilizing bridge-like structures.

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